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Knowledge Cannot Explain the Developmental Growth of Working Memory Capacity

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Abstract

According to some views of cognitive growth, the development of working memory capacity can account for increases in the complexity of cognition. It has been difficult to ascertain, though, that there actually is developmental growth in capacity that cannot be attributed to other developing factors. Here we assess the role of item familiarity. We document developmental increases in working memory for visual arrays of English letters versus unfamiliar characters. Although letter knowledge played a special role in development between the ages of 6 to 8 years, children with adequate letter knowledge showed practically the same developmental growth in normalized functions for letters and unfamiliar characters. The results contribute to a growing body of evidence that the developmental improvement in working memory does not wholly stem from supporting processes such as encoding, mnemonic strategies, and knowledge.

It is notoriously difficult to understand the basis of cognitive developmental maturation because multiple traits develop in concert. For this reason, there has been a continuing controversy regarding the improvement in cognitive abilities across childhood development. According to some researchers (who have been called neoPiagetian), the critical developmental growth is in the capacity of working memory, gauged by the number of schemes that can be kept active at once (Pascual-Leone & Smith, 1969; Pascual-Leone & Johnson, 2011) or by the number of elements that can interact with one another to form a concept (Halford, Cowan, & Andrews, 2007). (For further neoPiagetian perspectives see Morra, Gobbo, Marini, & Sheese, 2008). One problem with the idea of an increasing working memory capacity, though, is that it is quite difficult to separate from other developing traits. The present study was designed to separate capacity from the use of knowledge.

One research strategy to help determine whether capacity increases with age in childhood is to equate people across age groups in potentially confounding factors and to see whether the age difference in working memory ability disappears or remains. For example, Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) examined one such potentially confounding factor, the ability to exclude less-relevant items from working memory so as to use working memory most efficiently. They tested memory for the colors of items within

arrays that included two classes of items, those in a more-task-relevant shape (e.g., circles) and those in a less-task-relevant shape (e.g., triangles). Seven-year-old children were able to allocate more attention to the more-relevant shape, to the same extent that older children and adults did. Nevertheless, these young children remembered far fewer of the colors than did the children in the older groups. Cowan, AuBuchon, Gilchrist, Ricker, and Sauls (2011) were able to show that this age difference was not the result of encoding differences; when the items were presented one at a time at a slow rate, the pattern was unchanged. Nor was the effect a result of rehearsal in the older groups, inasmuch as requiring irrelevant articulation or requiring articulation of the perceived colors also left the pattern of results essentially unchanged.

A prime concern is the role of knowledge (e.g., Bjorklund, 1987; Kail, 1990; Miller, 2013). It appears that knowledge can be used in ways that greatly increase how much information can be recalled within immediate list-recall tasks, in adults (e.g., Ericsson, Chase, & Faloon, 1980) and in children (Chi, 1978). One way that this can happen is that ensembles of items bound together by knowledge can be simplified into a single unit to be remembered, or chunk (Miller, 1956). For example, a known acronym like *IRS* is memorized as a single unit and one can remember a list of, say, 3 of them without difficulty (e.g., *IRS-CIA-NSA*). We ask whether working memory performance develops similarly over childhood when one kind of knowledge, letter knowledge, is present versus absent.

We will review prior neoPiagetian research on the issue of capacity limits and then discuss our research strategy. As we then explain, we believe that the predictions are comparable no matter whether one adopts a modular view of working memory or a less-modular, embedded-process view. In either case, the results shed light on the issue of whether working memory capacity development can be explained as resulting from knowledge development.

NeoPiagetian Research on Working-Memory Capacity Limits

In a now-classic paper in cognitive development, Case, Kurland, and Goldberg (1982) eliminated age effects in a verbal working memory task by equating familiarity with the materials across age groups. They were able to equate 6-year-olds and adults in word span when adults were to remember nonsense words that they could only repeat at the same speed that 6-year-olds repeated real words. Repetition speed was viewed as a measure of operational efficiency. Then they did the same thing in a counting span task, by making adults count and remember numbers in an unfamiliar language. Adults counted in unfamiliar numbers at a rate similar to children with the familiar numbers, and remembered comparable list lengths as well. These results were taken to suggest that there is no developmental difference in capacity, only a difference in familiarity or knowledge of the materials that affects operational efficiency, which in turn determines the level of recall performance.

Although this study of Case et al. (1982) is quite compelling in many ways, it actually leaves the question of the basis of developmental change unanswered. Can it be attributed entirely to increases in knowledge, or is there something else? We do not know what the relation is between capacity and operational efficiency as defined in that article. In principle,

one relevant change still could be the number of working memory slots. To see why, suppose for example that each nonsense word presented to adults was represented as, on average, 2.0 chunks, whereas each real word presented to a child was represented as a single chunk. If that were the case, then apparently the time to enunciate each chunk was twice as fast in adults as in first-grade children; this could occur because the chunks within the nonsense words were phonologically shorter than the real words. Also according to that supposition, the adults must have recalled twice as many chunks as the children. Then an age difference in operational efficiency (measured by chunk-enunciation rate) would have been confounded by chunk length, and the basic difference would have been the number of chunks recalled. In support of this possibility, Cowan et al. (2006) were able to train children to recall digits at a rate equal to the rate that adults usually use, yet there was no change in span.

Even if Case et al. (1982) were correct in their theoretical account, their sequential presentation of verbal materials may have encouraged processes that depend on the speed of covert verbal rehearsal (Baddeley, 1986; Hulme & Tordoff, 1989), and the developmental results might not be the same for nonverbal materials that are less readily rehearsed. Note that Case (1995) himself re-evaluated the evidence and came out in favor of the development of basic working memory capacity. He relied heavily on unpublished results from S.A. Griffin, who trained children on number concepts and found that improvements in these were not accompanied by counting span or speed improvements. Neither span nor speed seemed to rely on number-processing ability, but rather, he surmised, on maturation. This analysis leaves open the causal path between span and speed.

Burtis (1982) carried out an elegant study leading to the conclusion that there is a developmental change in capacity itself, aside from differences in chunking ability. He presented matrices of letters grouped in pairs on several different bases to control chunking strategies: pairs having no prior association, pairs of identical letters, pairs that are familiar two-letter acronyms, pairs that became familiar over many repetitions, and pairs that stood out from the background because they were printed in red. Burtis concluded that, with chunking controlled across age groups, there was still a steady developmental increase in capacity. Morra (2000) extended the model to include phonological processing and rehearsal.

Case et al. (1982) could not be sure that the confluence of operational efficiency across age groups truly indicated that the operational efficiency was the reason for the developmental increase in performance (as explained above and in Case, 1995). Other research also is very consistent with the idea of an increase in capacity, though it also might be explained in other ways, given the complexity of results (e.g., Andrews, Halford, Bunch, Bowden, & Jones, 2003; Johnson, Im-Bolter, & Pascual-Leone, 2003).

The Present Research Approach

In the present work, we used a different logic to approach the question of the role of knowledge. First, we used an array-memory technique (Luck & Vogel, 1997), largely because it allows application of a known formula to estimate the number of items in working

memory (Cowan, 2001; Cowan et al., 2005). Memory for arrays of objects is known to improve during the elementary school years (Cowan et al., 2005; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Riggs, McTaggart, Simpson, & Freeman, 2006). Second, instead of just comparing more-familiar materials in children with less-familiar materials in adults, we compared the patterns of developmental improvement in memory for more-familiar materials (arrays of English letters) versus less-familiar materials (arrays of unfamiliar characters). We reduced the number of characters compared to the letters so that performance was in a similar range in both cases (at least for young children). Each array was followed by a single probe item that either was identical to the array item that appeared in the same screen location, or was not to be found anywhere in the array. The task was to indicate whether the item was present or absent from the array. This task is illustrated for unfamiliar characters in Figure 1.

If knowledge alone accounts for developmental increases in ability, an extreme prediction is that there might be no developmental increase at all in performance on the unfamiliar characters. That prediction is not assured, however, inasmuch as older participants might use their world knowledge to think of mnemonics for some of the unfamiliar characters. At the least, we should be able to trust that world knowledge can be applied in the case of English letters more easily than it can be applied in the case of unfamiliar characters. The English letters could be covertly rehearsed (Baddeley, 1986) or more elaborate mnemonics could be applied (e.g., *ZRC=Zebra made of Rock Candy*). Familiarity with the letters should make them easier to recall than unfamiliar characters are, because each letter can be encoded as a single chunk whereas a single unfamiliar character might require multiple chunks. (For example, in the bottom character of the array in Figure 1, perhaps the curved top line and the b-shaped portions must be held in working memory separately.)

When knowledge differences contribute to performance differences, the extent of developmental improvement, examined across conditions using normalized scores, should be steeper for the letters than for the characters. We might especially expect this to be the case in the early grades of elementary school, when the letters are not well-known. If the main source of the development of working memory capacity in the more advanced grades is not caused by familiarity, however, there could be no difference between the normalized developmental functions for the unfamiliar characters versus known letters.

We also varied the retention interval separating the array to be remembered and subsequent probe item test. Previously, using lists of verbal items unattended at the time of their presentation (preventing rehearsal), we found an age difference in the rate of forgetting across retention intervals of 1, 5, or 10 s for the final item, but no age difference in forgetting of previous list items (Cowan, Nugent, Elliott, & Saults, 2000). It is unclear whether a visual array will be more like a single, final item, producing age differences in forgetting over time, or will be more like an entire list, producing no such age differences. In either case, the outcome will be informative, for at least two reasons.

First, it is unclear whether English letters within arrays are maintained in working memory by older participants through covert verbal rehearsal. Based on list memory studies, this kind of maintenance strategy would be expected for the older groups but not the younger ones,

with increasing sophistication as a function of maturation (e.g., Flavell, Beach, & Chinsky, 1966; Ornstein, Naus, & Liberty, 1975). If so, memories of English letters should be lost more slowly across retention intervals in older groups than in younger ones, to a greater extent than is found for unrehearsable, unfamiliar characters. It is not known, we believe, whether covert verbal rehearsal plays much of a role for arrays of verbal items. Morey (2009) did find that suppressing articulation diminished adults' memory for arrays of English letters. It is unclear, however, whether that effect reflects the use of articulation to rehearse phonological codes, which only more advanced participants are likely to do; or whether it only reflects the formation of phonological codes from the printed letters in the first place, which even a relatively young child who can read letters may do. Therefore, the present examination of the persistence of information across retention intervals might reveal important information about the possible use of rehearsal in older participants.

Second, the possibility of change in memory loss across retention intervals also has implications for how well the information was consolidated in memory. Ricker and Cowan (in press) found that forgetting across a retention interval in adults was reduced or eliminated when participants had a certain amount of time to attend to each item before having to attend to something else; this attention period was called the consolidation time. Although we do not yet know exactly what processes contribute to this kind of consolidation, if there are no age differences in loss over retention intervals, it will be difficult to argue that the basis of developmental change in working memory is an increase in the adequacy of such processes.

Comparable Predictions Based on Two Types of Working-Memory Theory

Before getting further into methodology, we wish to explain our belief that the logic of the research holds up under a variety of assumptions about the nature of working memory. We discuss the predictions here in relation to two theoretical views of working memory, the modular view of Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley, 2000; Logie, 1986; Logie, Della Sala, Wynn, & Baddeley, 2000) and the embedded-process view of Cowan (1988, 1995, 1999, 2001, 2005).

According to the most popular modular view of Baddeley and colleagues (e.g., Baddeley, 2000), both unfamiliar characters and English letters should give rise to a representation in a store called the visuospatial sketchpad. Additionally, when letter knowledge allows the materials to give rise to a speech-based representation, as letters would do for literate participants, information is saved in a phonological representation. The capacity of the phonological representation is said to be in terms of the time that an item is presumed to persist since the most recent presentation or rehearsal of the material; in adults, about 2 s. It can be assumed that correct recognition could occur if the necessary information is present in either the phonological or the visuospatial store. The capacity of the visuospatial sketchpad has not been specified. If a young child is preliterate, he or she should be disadvantaged for letter stimuli by the absence of a phonological representation or the ability to rehearse it.

So far, these suggestions pertain to representations and strategies that relate to letter knowledge. They say nothing about a possible increase with age in the ability to retain unfamiliar characters. If, however, the visuospatial sketchpad improves with age, it could result in an improvement in memory for both letters and characters with age.

According to the version of the modular approach proposed by Baddeley (2000) as an amendment to his somewhat earlier views (but not truly discrepant from Baddeley & Hitch, 1974), there is also an episodic buffer that can retain concepts, and can retain the binding between phonological and visuospatial information. A developmental improvement in this store, too, could result in developmental increases in memory for either verbal or nonverbal, visual information.

The view of Cowan (e.g., Cowan, 2005) is one in which separate modules are not specified. There is more concern in that approach that the taxonomy of stores, if they are separate, is more complex (e.g., including the information in spatial arrays of sounds, tactile stimuli, or non-phonological tone patterns). Instead of specifying modules, Cowan proposed that all sorts of stimuli give rise to the activation of various sorts of features in long-term memory (phonological, orthographic, and semantic features for example). These features were assumed to be lost at a similar rate over some seconds unless they were rehearsed. Interference was said to occur between items with similarities in features on any level. There also was assumed to be memory storage of several separate, integrated, meaningful units at most in the focus of attention, with developmental change in the number of units that could be held in this fashion (with a maximum of 3 to 5 units on average in adults, depending on methodological details, versus only about 2 to 3 items in children about 7 years of age, i.e., in our youngest age group). Covert verbal rehearsal is said to perpetuate items in working memory with little devotion of attention (at least for verbal lists) but it is deficient in young children. At least for unfamiliar characters, though, there is evidence that suppressing rehearsal has little effect on adult performance (Ricker et al., 2010).

From either of these theoretical vantage points, the theoretical predictions for the present research are similar. First, young children should be relatively deficient in the advantage for English letter memory compared to memory for unfamiliar characters because of their relative unfamiliarity with letters. The phonological representation constructed more successfully for letters among older children and adults should assist their memory for letters.

Second, even for unfamiliar characters that cannot easily be retained with a mnemonic strategy, there should be a developmental increase in performance if, as has been assumed, there is a developmental increase in the capacity of one or more relevant storage mechanism (e.g., Baddeley's visuospatial sketchpad or Cowan's focus of attention).

Third, at the point in development after the phonological representations of letters are well-established, the developmental trajectory for letters and characters could be similar, with both of them dependent on developmental changes in the capacity and/or persistence of memory in the relevant storage mechanism or mechanisms. Alternatively, if letters in arrays can be usefully rehearsed by older participants, that should result in a more severe

developmental trajectory for letters than for unfamiliar characters, with a relative jump in letter performance as rehearsal matures sometime in the middle of the elementary school years (Flavell et al., 1966; Ornstein et al., 1975), along with less forgetting over retention intervals.

Method

Participants

The sample that completed the experiment consisted of 26 individuals in each of 4 age groups (total N=104): Grades 1–2, Mean age = 7.23 years, SD=0.59; Grades 3–4, Mean age = 9.27 years, SD=0.85; Grades 5–7, Mean age = 11.93 years, SD=0.72; and college students, Mean age = 24.54 years, SD=8.90. Of these, the number of females in the four age groups, respectively, was 20, 11, 14, and 13. An additional 5 participants were lost because of experimenter error or computer malfunction (4 in Grades 1–2 and 1 in Grades 5–7), and 2 additional children in Grades 1–2 failed to finish the experiment.

Apparatus, Stimuli, and Procedure

In the array memory task, each participant completed all trials with either English letters or unfamiliar characters first, followed by the other memoranda type in the second half of the session. Half of each age group received each of the two test orders. We settled on arrays of 3 characters as the minimal number needed to assess capacity, yet a number that does not result in ceiling effects in adults (Ricker et al., 2010). Ricker and Cowan (2010), previously found that, in adults, comparable performance levels were obtained using arrays of 6 English letters but, fearing floor effects in young children, we reduced the arrays to 5 letters as a compromise value that would avoid floor effects in the youngest children, as we knew from previous work with arrays of nameable colors (Cowan et al., 2010, 2011). This decision proved to result in roughly comparable performance levels across materials in the youngest age group.

For each memoranda type (unfamiliar characters and English letters) there were 10 practice trials, including 5 trials with a 1-s retention interval followed by 5 trials with a 5-s retention interval, and then 72 test trials of that type divided into two blocks of 36 trials. Within each block, there were six kinds of trials equally represented in random order: change and no-change trials using each of three retention intervals (1, 5, or 10 s). Thus, there were 144 (=4×36) test trials in all.

A trial with unfamiliar characters is illustrated in Figure 1. Each trial was initiated by the participant pressing the space bar. A single trial consisted of presentation of a fixation cross at the center of the screen, which remained on the screen for the entire trial. After 500 ms of the fixation cross, an array of characters (reference array) appeared for 750 ms and was to be remembered. It consisted of either 3 unfamiliar characters or 5 English letters presented at random location on the screen (within confines described below). After the reference array there was a 250 ms period in which the screen was blank with the exception of the fixation cross, which ended with the presentation of a mask 100 ms in duration. The mask consisted of the “<” and “>” symbols superimposed on top of one another, with their line widths and

total size roughly equal to that of the characters, at each location on the screen where an array item had been presented. The mask was included because the short, literal sensory afterimage of several hundred milliseconds from which working memory information is extracted appears to be followed by a second phase of sensory memory, a vivid recollection of sensation lasting up to several seconds that is also susceptible to a mask (see Cowan, 1988, 1995; Saults & Cowan, 2007).

Following mask offset there was a retention interval of 1, 5, or 10 s. During the retention interval only the fixation cross remained on the screen. After the retention interval ended a single, probe item was presented at the location of one of the items in the reference array. On half of the trials, this probe item was the same as the item originally shown in that location during the array. On the other half of the trials, the probe item presented at that location was a new item. Participants were instructed to press the “s” key if the item was the same as the item presented at that location during the reference array, or to press the “d” key if the item was different. Participants were informed that when the item was different, it would be an item that did not appear anywhere in the reference array. The spatial locations of items thus could be ignored, much as the temporal locations can be ignored in a typical list-search task (Sternberg, 1969). The probe item remained on screen until the participant made a response. When a response was made, feedback was presented immediately. The feedback screen consisted of the presentation of a simplified face drawing for 750 ms. If the participant was correct, a smiley face was presented in yellow and accompanied by a high pitch tone. If the participant was incorrect, a frowning face was presented in purple and accompanied by a low pitch tone.

The locations used in the reference array were within an area of 15.3 by 11.5 degrees of visual angle centered at the center of the computer screen. Unfamiliar characters were roughly 2.3 by 2.3 degrees of visual angle in size, while English Letters were roughly 1.4 by 0.9 degrees of visual angle. The unfamiliar character set consisted of 231 characters selected from alphabets and numeral systems not used in English. Each character was carefully screened to be sure that it did not resemble any English letters or numerals, then turned 90 degrees before presentation. The English letter set consisted of all English letters. Each item was selected at random, without replacement, on each trial, from the full set of letters or characters. Items used as different probes were also selected at random from the full item set, excluding items used in the reference array. A minimal distance was imposed such that the center-to-center locations of any two items could not be less than 128 pixels.

Results

The results are presented first raw as the proportion correct, and then with modeling of the number of items in working memory, intended to guide theoretical conclusions.

Proportion Correct

The proportions correct in all conditions of the experiment are shown in Table 1. They were subjected to an ANOVA with all of the factors shown in the table. There was a steady progression of performance across age groups ($M=.59, .69, .74, \& .83$, respectively), $F(3,100)=45.53$, $p<.001$, $\eta_p^2=.58$; a large advantage for English letters ($M=.76$) over

unfamiliar characters ($M=.66$), $F(1,100)=110.53$, $p<.001$, $\eta_p^2=.53$; a loss across increasing retention intervals ($M=.76$, $.70$, & $.68$), $F(2,200)=32.06$, $p<.001$, $\eta_p^2=.24$; and an advantage for change trials ($M=.78$) over no-change trials ($M=.65$), $F(1,100)=75.58$, $p<.001$, $\eta_p^2=.43$.

Among the interactions, the most important was an interaction of age group with the type of stimuli, unfamiliar characters versus English letters, $F(3,100)=11.52$, $p<.001$, $\eta_p^2=.26$. Our attempts at matching the stimuli across types resulted in performance being nearly the same for characters and letters in the youngest age group (e.g., at a 1-s retention interval: characters, $.62$; letters, $.63$). With age, performance increased for letters more quickly than it increased for characters.

The three-way interaction of age \times stimulus type \times retention interval did not approach significance, $F(6,200)<1$, $\eta_p^2=.02$. There also were interactions that will not be reported in detail because they were deemed unimportant, in that they did not involve age group as a factor: interactions of the type of material by the presence or absence of change; the retention interval by presence or absence of change; and a three-way interaction between these variables. The four-way interaction was significant but will not be interpreted.

Although some no-change scores in Table 1 (correct rejections) are near 0.50, that fact cannot be said to reflect chance performance. Accuracy on any kind of trial depends both on the ability to detect the presence or absence of change and on the response bias. Provided that the average of the proportion of hits and correct rejections for a particular trial type exceeds 0.50, performance should be viewed as above chance. For every age group in every condition, this average did significantly exceed chance, in that the 95% confidence interval for each such average did not cover 0.50 and was always above it.

Items in Working Memory

A model first reported by Cowan (2001) was designed to estimate items in working memory, k , in procedures like the present one. If there are S items in the array and the participant can remember k of them, then the participant will know the answer to the probe in k/S of the trials in which there was a change and in k/S of the trials in which there was no change. When the participant does not know, which occurs on $1-k/S$ of the trials, the probability is g that he or she will guess that there was a change. That is, when there was a change, the probability of being correct is $p(\text{hit})=k/S+(1-k/S)g$ and when there was no change, the probability of being incorrect is $p(\text{false alarm})=(1-k/S)g$. Combining these equations, $k=S[p(\text{hit})-p(\text{false alarm})]$.

As in the proportion correct, there was no evidence for a floor effect in these scores. Chance performance would be $k=0$. For each age group, the mean k value in each of six conditions (unfamiliar characters versus English letters and retention intervals of 1, 5, or 10 s) was positive and the 95% confidence interval did not overlap with zero. In the lowest score, which was for first-grade children with characters at a 10-s interval, the confidence interval for k ranged from 0.07 to 0.60 items. This evidence is not independent of the proportion correct results reported above, inasmuch the k score is a linear transformation of the average of hits and correct rejections.

Further results for items in working memory will be presented first for the shortest, 1-s retention interval in order to estimate items in working memory before forgetting can occur. Then we will examine the effects of retention interval separately, to assess forgetting.

Group differences at the 1-s retention interval—The most important analyses with k values were carried out on the short, 1-s retention interval data to determine the number of items encoded into working memory before there was much time for forgetting to take place. The results of this analysis are shown in Table 2. There were large main effects of age group, $F(3,100)=36.15$, $p<.001$, $\eta_p^2=.52$, and stimulus type, $F(1,100)=244.65$, $p<.001$, $\eta_p^2=.71$. Most importantly, these factors interacted, $F(3,100)=13.72$, $p<.001$, $\eta_p^2=.29$. The basis of this interaction is that, for 1-s data, as shown in the table, the advantage of letters over characters grew larger with age.

One reason for the advantage of letters over the characters might be that each character must be retained as more than one chunk, which would produce a ratio of performance between characters and letters. For the three older groups, a ratio of roughly 3 letters retained in working memory for every character retained seems to hold. This ratio does not apply, though, for children in the youngest age group, for whom the ratio is approximately 2:1. This departure from the rule suggests that children in the youngest age group either have less letter knowledge or, at least, are less able to make use of that knowledge for maintenance of the letters in working memory. This, of course, makes sense in that many children typically begin to be literate only in Grade 1 (around 7 years of age).

To remove the most severe differences in letter knowledge, we carried out additional analyses only on children who were able to retain at least 1.0 letter, on average, in the 1-s condition, the presumption being that retention of fewer than that indicates poor letter knowledge. The number of children passing that criterion out of a total of 26 per group was 16, 23, 25, and 26 in the four age groups, respectively. Figure 3 shows that, with this subgroup, the ratio between conditions is much less variable across age groups.

When two measures have different scaling properties, it is often helpful to normalize them before drawing conclusions by comparing them. In Figure 3, for example, one can see that the adults perform on letters at a level that is above the ceiling for the characters (3.0). After normalizing scores, Gathercole et al. (2004) showed a beautiful developmental trend from 4 to 15 years, which was quite similar across measures (see also Alloway, Gathercole, & Pickering, 2006). These measures, however, did not systematically differ on the amount of knowledge needed to retain the stimuli.

We normalized k scores of the select group shown in Figure 3 for the 1-s retention interval, separately for characters and letters. Both of these normalization processes involved the calculation of z scores across all age groups, so only two distributions were used to calculate z scores. For each condition, therefore, an individual's z score expresses where the participant stands on that condition relative to all other participants in the analysis, not just the participant's own age group. The results are shown in Figure 4. An analysis of these z scores revealed an effect of age group, $F(3,86)=23.01$, $p<.001$, $\eta_p^2=.45$, but no effect of the type of stimulus, $F<1$, $\eta_p^2=.00$, or its interaction with age group, $F<1$, $\eta_p^2=.03$.

We also carried out an analysis in which we omitted the youngest age group but used z scores for all 26 participants in the higher 3 age groups. This analysis yielded only an effect of age group, $F(2,75)=19.66$, $p<.001$, $\eta_p^2=.34$. There was no significant difference between characters and letters, $F(1,75)=2.59$, $p=.11$, n.s., $\eta_p^2=.03$, and their interaction with age did not approach significance, $F<1$, $\eta_p^2=.01$. Thus, when age differences in letter knowledge or its mnemonic use are minimized, there appears to be a striking developmental growth in capacity that cannot be attributed to growing knowledge of English letters; knowledge growth within this older age range accounted for only a small and insignificant proportion of the variance.

Effects of retention intervals—Performance across retention intervals yields important information about the stability of information in working memory. If older participants rehearse the English letters, they should retain these stimuli over a longer period than younger participants. If better encoding and consolidation in older participants is involved, then the results of Ricker and Cowan (in press) suggest that older participants should show less forgetting across retention intervals for both types of stimuli.

We analyzed the items in working memory across retention intervals in all participants but, given possible concerns about low performance levels in some participants at the longer retention intervals, we divided each age group into an upper half and a lower half according to overall proportion correct. An ANOVA was carried out with two between-participant factors: the age group and the upper versus lower half assignment for that age group. Within-participant factors included the type of stimuli (letters versus characters) and the retention interval (1, 5, or 10 s). Only effects involving the retention interval were of theoretical importance. There was a main effect of retention interval, $F(2,192)=28.35$, $p<.001$, $\eta_p^2=.23$, but retention interval did not come close to a significant interaction with any other factor or combination of factors, $p>.12$ and $\eta_p^2<.05$ in each case.

Figure 5 shows the number of items in working memory as a function of the age group (left-hand panel) and as a function of the performance half within an age group (right-hand panel). It is clear that these factors did not influence the rate of forgetting substantially, although there is a slight, non-significant trend for the adults and the upper half of each age group to forget more slowly. Overall, then, there is little or no evidence of the development of processes that would make array items last longer in working memory for older participants.

Discussion

The present study shows that there is a contribution to letter knowledge, or mnemonic use of that knowledge, to working memory but that, when the contribution of knowledge is minimal, there is still a dramatic increase in working memory capacity. That was the case for unfamiliar characters, for which there should be little relevant knowledge even in adults. Moreover, when participants were selected to filter out children with insufficient letter knowledge, the same developmental trend can be seen across both English letters and unfamiliar characters (in the normalized curves of Figure 4). The developmental increase in the z score of the estimated number of items in working memory is comparable for both

types of material. This evidence adds to other findings suggesting that working memory capacity increases with age in childhood. The evidence is that developmental improvements in processes other than capacity are not enough to account for performance increases in working memory tasks (Burtis, 1982; Case, 1995; Gilchrist, Cowan, & Naveh-Benjamin, 2009; Cowan et al., 2010, 2011).

More work would be necessary to understand the letter knowledge factor that was a barrier for some of the younger children. It is possible that these young children did not yet know their letters well. Alternatively, perhaps they knew their letters but were unable to combine the phonological information about the letters with the visual information in order to make both types of memory useful together (as in the binding function of the episodic buffer of Baddeley, 2000 or the focus of attention of Cowan, 1988, 1999). A comparable question arose for Darling, Parker, Goodall, Havelka, and Allen (2014), who found that 6-year-olds could not make use of the presentation of digits to be remembered in the form of a standard keyboard as opposed to a novel configuration, whereas 9-year-old children could do so. Comparable to our result for letter knowledge, it was not clear whether the younger children did not know the keyboard configurations, or knew them but were unable to combine the information with digit memory.

Another unresolved issue of importance is the role of covert verbal rehearsal in development. It has long been known that such rehearsal becomes more sophisticated with development (Flavell et al., 1966; Ornstein et al., 1975). Hitch, Halliday, Dodd, and Littler (1989) suggested that rehearsal itself does not develop (inasmuch as word length effects in recall occurred for children as young as 4 years of age given spoken words), but that rehearsal cannot be used for pictured objects until about 8 years. The speech-based effect in younger children, however, could be the result of the degradation of memory during the recall period, which lasts longer for longer words. If a pointing response is used, the word length effect is not seen until 7 or so years of age (Henry, 1991). Finally, a recent study suggests that the apparent role of covert rehearsal in development could result from psychometric scaling problems in comparisons across age groups in recall (Jarrold & Citroën, 2013). We cannot resolve this controversy but, in any case, we find it unlikely that rehearsal plays much of a role in the present study, inasmuch as articulatory suppression on one study did not change the developmental results in memory for arrays of nameable colors (Cowan et al., 2011).

The absence of an age difference in the rate of loss of memory over time (Figure 5) also reinforces a finding of Cowan et al. (2011) that the age difference was not in the ability to maintain representations through covert verbal rehearsal, as that should have resulted in more persistence of memory for letters in older participants than in younger ones.

Another recent study examined the role of knowledge in a very different type of working memory task. Gilchrist et al. (2009) examined knowledge in the form of chunking effects by presenting sets of unrelated, simple sentences for verbatim recall, using as a measure of chunking knowledge the proportion of a sentence that was recalled, given that any of it was recalled. Although this proportion was stable at about 80% between first grade (7-year-olds) and adulthood, the number of sentences that were at least partly recalled did increase

substantially with development across that age range. The present evidence reinforces the findings of Gilchrist et al. (2009) that knowledge cannot account for working memory development, using very different materials: arrays of characters or letters as opposed to the spoken sentences that Gilchrist et al. used. Clearly, in the real world, there are vast improvements in knowledge with age, and they have strong effects on working memory performance in the real world, but we have identified improvements that cannot be attributed to knowledge. This is important if it is the case that working memory capacity helps to set an upper bound on the complexity of ideas that can be understood by developing children (Halford et al., 2007).

This evidence that knowledge cannot fully account for developmental differences in working memory ability must be added to evidence that other confounding factors cannot account for these developmental differences either, including improvements in the ability to filter out less-relevant information and allocate attention to the most-relevant information (Cowan et al., 2010), to encode information into working memory, or to rehearse that information (Cowan et al., 2011).

Although there has been considerable debate in the adult literature about the existence of decay of unrehearsed working memory representations over time, Ricker and Cowan (in press) showed that adults display much greater decay for relatively poorly-consolidated items. Those were items that were presented and then followed shortly afterward by some other stimulus that had to be attended. If older participants had consolidated the items better than younger ones, the information should have been more stable across retention intervals. The fact that the rate of loss was so similar across age groups rules out consolidation as the basis of developmental difference here. Thus, by process of elimination, we are beginning to establish a role for capacity increases (cf. Pascual-Leone & Johnson, 2011).

It will take more work to identify what theoretical constructs could account for a developmental course for memory of arrays of unfamiliar characters and English letters that are the same once English letter knowledge is established. In the model of Baddeley (2000), the simplest solution would be an increase in the capacity of the episodic buffer, a single store that can accommodate various kinds of materials. If that is not the solution, it would alternatively be possible to posit comparable rates of developmental growth in the phonological loop (for English letters) and visuospatial sketchpad (for unfamiliar characters). One might have expected, however, that these developmental changes would show up in terms of the loss of information across the retention interval, which did not differ across ages. In the model of Cowan (1988, 1999, 2001), the absence of changes in forgetting across ages goes against activated long-term memory as the source of developmental change, as it is supposed to be susceptible via decay, and favors instead development of the capacity of the focus of attention (cf. Cowan et al., 2005).

One remaining possibility that remains unchecked is that it could be the precision of the representations, rather than the number of representations, that increases with childhood development. We previously found a developmental improvement in precision for tones in working memory (Keller & Cowan, 1994). Recently, Heyes, Zokaei, van der Staaij, Bays, and Husain (2012) found a developmental improvement in the precision of representations

of the orientation of bars. Even for our arrays of English-letter stimuli, as well as our unfamiliar characters, it is possible that a more detailed representation preserves spatial relations in a non-verbal manner that can supplement categorical information to serve as cues to the stimuli, much like the visual bootstrapping of verbal information suggested by Darling et al. (2014).

A conclusive investigation of this issue of what develops (capacity and precision, or precision only?) probably must await resolution of an ongoing debate on the nature of adult function. The issue is whether working memory capacity is limited to a discrete number of objects (Anderson, Vogel, & Awh, 2011; Cowan & Rouder, 2009; Donkin, Nosofsky, Gold, & Shiffrin, 2013; Rouder et al., 2008; Zhang & Luck, 2011), limited to a finite but fluctuating number of objects (van den Berg, Awh, & Ma, 2014), or limited by a fluid resource that can be distributed across any number of objects, with precision decreasing as the number of objects increases (Bayes & Husain, 2008; van den Berg, Shin, Chou, George, & Ma, 2012; Gorgoraptis, Catalao, Bays, & Husain, 2011). The solution of this issue is likely to help determine the methods that will be most suitable to investigate the development of working memory. If the present results are confirmed in other work, they will motivate a major shift in how the field views cognition and cognitive development, amplifying the role of working memory capacity among other factors. In a practical sense, knowing the basis of working memory development is important if we are to construct educational systems that help children maximize their intellectual development (cf. Diamond & Lee, 2011).

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References

- Alloway TP, Gathercole SE, Pickering SJ. Verbal and visuospatial short-term and working memory in children: are they separable? *Child Development*. 2006; 77:1698–1716. [PubMed: 17107455]
- Anderson DE, Vogel EK, Awh E. Precision in visual working memory reaches a stable plateau when individual item limits are exceeded. *The Journal Of Neuroscience*. 2011; 31:1128–1138. [PubMed: 21248137]
- Andrews G, Halford GS, Bunch KM, Bowden D, Jones T. Theory of mind and relational complexity. *Child Development*. 2003; 74:1476–1499. [PubMed: 14552409]
- Baddeley, AD. *Working memory*. Oxford, England: Clarendon Press; 1986.
- Baddeley A. The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*. 2000; 4:417, 423. [PubMed: 11058819]
- Baddeley A. The magic number and the episodic buffer. *Behavioral and Brain Sciences*. 2001; 24:117, 118.
- Bays PM, Husain M. Dynamic shifts of limited working memory resources in human vision. *Science*. 2008; 321:851, 854. [PubMed: 18687968]
- Bjorklund DF. How age changes in knowledge base contribute to the development of children's memory: An interpretive review. *Developmental Review*. 1987; 7:93–130.
- Burtis PJ. Capacity increase and chunking in the development of short-term memory. *Journal of Experimental Child Psychology*. 1982; 34:387–413. [PubMed: 7153702]

- Case, R. Capacity based explanations of working memory growth: A brief history and reevaluation. In: Weinert, FE.; Schneider, W., editors. *Memory performance and competencies: Issues in growth and development*. Mahwah, NJ: Erlbaum; 1995. p. 23-44.
- Case R, Kurland DM, Goldberg J. Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*. 1982; 33:386–404.
- Chi, MTH. Knowledge structures and memory development. In: Siegler, R., editor. *Children's thinking: What develops?*. Hillsdale, NJ: Erlbaum; 1978.
- Conway ARA, Kane MJ, Bunting MF, Hambrick DZ, Wilhelm O, Engle RW. Working memory span tasks: A methodological review & user's guide. *Psychonomic Bulletin & Review*. 2005; 12:769–786. [PubMed: 16523997]
- Cowan N. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*. 1988; 104:163–191. [PubMed: 3054993]
- Cowan, N. *Attention and memory: An integrated framework*. New York: Oxford University Press; 1995. Oxford Psychology Series (No. 26)
- Cowan, N. An embedded-processes model of working memory. In: Miyake, A.; Shah, P., editors. *Models of Working Memory: Mechanisms of active maintenance and executive control*. Cambridge, U.K: Cambridge University Press; 1999. p. 62-101.
- Cowan N. The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*. 2001; 24:87–185. [PubMed: 11515286]
- Cowan, N. *Working memory capacity*. Hove, East Sussex, UK: Psychology Press; 2005.
- Cowan N, AuBuchon AM, Gilchrist AL, Ricker TJ, Saults JS. Age differences in visual working memory capacity: Not based on encoding limitations. *Developmental Science*. 2011; 14:1066–1074. [PubMed: 21884322]
- Cowan N, Elliott EM, Saults JS, Morey CC, Mattox S, Hismjatullina A, Conway ARA. On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*. 2005; 51:42–100. [PubMed: 16039935]
- Cowan N, Elliott EM, Saults JS, Nugent LD, Bomb P, Hismjatullina A. Rethinking speed theories of cognitive development: Increasing the rate of recall without affecting accuracy. *Psychological Science*. 2006; 17:67–73. [PubMed: 16371146]
- Cowan N, Morey CC, AuBuchon AM, Zwilling CE, Gilchrist AL. Seven-year-olds allocate attention like adults unless working memory is overloaded. *Developmental Science*. 2010; 13:120–133. [PubMed: 20121868]
- Cowan N, Naveh-Benjamin M, Kilb A, Saults JS. Life-Span development of visual working memory: When is feature binding difficult? *Developmental Psychology*. 2006; 42:1089–1102. [PubMed: 17087544]
- Cowan N, Nugent LD, Elliott EM, Saults JS. Persistence of memory for ignored lists of digits: Areas of developmental constancy and change. *Journal of Experimental Child Psychology*. 2000; 76:151–172. [PubMed: 10788307]
- Cowan N, Rouders JN. Comment on "Dynamic Shifts of Limited Working Memory Resources in Human Vision". *Science*. 2009 Feb 13;323:877c. [PubMed: 19213899]
- Darling S, Parker MJ, Goodall KE, Havelka J, Allen RJ. Visuospatial bootstrapping: Implicit binding of verbal working memory to visuospatial representations in children and adults. *Journal of Experimental Child Psychology*. 2014; 119:112–119. [PubMed: 24287442]
- Deary IJ, Whalley LJ, Lemmon H, Crawford JR, Starr JM. The stability of individual differences in mental ability from childhood to old age: follow-up of the 1932 Scottish Mental Survey. *Intelligence*. 2000; 28:49–55.
- Diamond A, Lee K. Interventions shown to aid executive function development in children 4 to 12 years old. *Science*. 2011; 333:959–964. [PubMed: 21852486]
- Donkin C, Nofskey RM, Gold JM, Shiffrin RM. Discrete slot models of visual working-memory response times. *Psychological Review*. 2013; 4:873–902. [PubMed: 24015956]
- Ericsson KA, Chase WG, Faloony S. Acquisition of a memory skill. *Science*. 1980; 208:1181–1182. [PubMed: 7375930]

- Flavell JH, Beach DH, Chinsky JM. Spontaneous verbal rehearsal in a memory task as a function of age. *Child Development*. 1966; 37:283–299. [PubMed: 5941895]
- Gathercole SE, Pickering SJ, Ambridge B, Wearing H. The structure of working memory from 4 to 15 years of age. *Developmental Psychology*. 2004; 40:177–190. [PubMed: 14979759]
- Gilchrist AL, Cowan N, Naveh-Benjamin M. Investigating the childhood development of working memory using sentences: New evidence for the growth of chunk capacity. *Journal of Experimental Child Psychology*. 2009; 104:252–265. [PubMed: 19539305]
- Gorgoraptis N, Catalao RG, Bays PM, Husain M. Dynamic updating of working memory resources for visual objects. *The Journal Of Neuroscience*. 2011; 31:8502–8511. [PubMed: 21653854]
- Halford GS, Cowan N, Andrews G. Separating cognitive capacity from knowledge: A new hypothesis. *Trends in Cognitive Sciences*. 2007; 11:236–242. [PubMed: 17475538]
- Heyes SB, Zokaei N, van der Staaij I, Bays PM, Husain M. Development of visual working memory precision in childhood. *Developmental Science*. 2012; 15:528–539. [PubMed: 22709402]
- Henry LA. The effects of word length and phonemic similarity in young children's short-term memory. *Quarterly Journal of Experimental Psychology*. 1991; 43A:35–52.
- Hitch GJ, Halliday MS, Dodd A, Littler JE. Development of rehearsal in short term memory: Differences between pictorial and spoken stimuli. *British Journal of Developmental Psychology*. 1989; 7:347–362.
- Hulme C, Tordoff V. Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall. *Journal of Experimental Child Psychology*. 1989; 47:72–87.
- Jarrold C, Citroën R. Reevaluating key evidence for the development of rehearsal: Phonological similarity effects in children are subject to proportional scaling artifacts. *Developmental Psychology*. 2013; 49:837–847. [PubMed: 22662766]
- Johnson J, Im-Bolter N, Pascual-Leone J. Development of mental attention in gifted and mainstream children: The role of mental capacity, inhibition, and speed of processing. *Child Development*. 2003; 74:1594–1614. [PubMed: 14669884]
- Kail, R. The development of memory in children. 3. NY: W.H. Freeman; 1990.
- Keller TA, Cowan N. Developmental increase in the duration of memory for tone pitch. *Developmental Psychology*. 1994; 30:855–863.
- Logie RH. Visuo spatial processing in working memory. *Quarterly Journal of Experimental Psychology*. 1986; 38A:229–247. [PubMed: 3737975]
- Logie RH, Della Sala S, Wynn V, Baddeley AD. Visual similarity effects in immediate verbal serial recall. *Quarterly Journal of Experimental Psychology*. 2000; 53A:626–646. [PubMed: 10994221]
- Luck SJ, Vogel EK. The capacity of visual working memory for features and conjunctions. *Nature*. 1997; 390:279–281. [PubMed: 9384378]
- Miller GA. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*. 1956; 63:81–97. [PubMed: 13310704]
- Miller, PH. The history of memory development research: Remembering our roots. In: Bauer, PJ.; Fivush, R., editors. *The Wiley Handbook on the development of children's memory*. Wiley-Blackwell; 2013.
- Morey CC. Integrated cross-domain object storage in working memory: Evidence from a verbal-spatial memory task. *Quarterly Journal of Experimental Psychology*. 2009; 62:2235–2251.
- Morra S. A new model of verbal short-term memory. *Journal Of Experimental Child Psychology*. 2000; 75:191–227. [PubMed: 10666325]
- Morra, S.; Gobbo, C.; Marini, Z.; Sheese, R. *Cognitive development: Neo-Piagetian perspectives*. New York, NY: Taylor & Francis Group/Lawrence Erlbaum Associates; 2008.
- Ornstein PA, Naus MJ, Liberty C. Rehearsal and organizational processes in children's memory. *Child Development*. 1975; 46:818–830.
- Pascual-Leone, J.; Johnson, J. A developmental theory of mental attention: Its applications to measurement and task analysis. In: Barrouillet, P.; Gaillard, V., editors. *Cognitive development and working memory: From neoPiagetian to cognitive approaches*. Hove, UK: Psychology Press; 2011. p. 13-46.

- Pascual-Leone J, Smith J. The encoding and decoding of symbols by children: A new experimental paradigm and a neo-Piagetian model. *Journal of Experimental Child Psychology*. 1969; 8:328–355.
- Raven, J.; Raven, JC.; Court, JH. *Raven Manual: Section 3. Standard Progressive Matrices Including the Parallel and Plus versions*. 2000 Edition. Oxford, UK: Oxford Psychologists Press; 1998.
- Ricker TJ, Cowan N. Loss of visual working memory within seconds: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2010; 36:1355–1368.
- Ricker TJ, Cowan N. Differences between presentation methods in working memory procedures: A matter of working memory consolidation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. in press.
- Ricker TJ, Cowan N, Morey CC. Visual working memory is disrupted by covert verbal retrieval. *Psychonomic Bulletin & Review*. 2010; 17:516–521. [PubMed: 20702871]
- Riggs KJ, McTaggart J, Simpson A, Freeman RPJ. Changes in the capacity of visual working memory in 5 to 10-year-olds. *Journal of Experimental Child Psychology*. 2006; 95:18–26. [PubMed: 16678845]
- Rouder JN, Morey RD, Cowan N, Zwilling CE, Morey CC, Pratte MS. An assessment of fixed-capacity models of visual working memory. *Proceedings of the National Academy of Sciences (PNAS)*. 2008; 105(16):5975–5979.
- Sternberg S. Memory scanning: Mental processes revealed by reaction time experiments. *American Scientist*. 1969; 57:421–457. [PubMed: 5360276]
- Towse JN, Hitch GJ, Horton N, Harvey K. Synergies between processing and memory in children's reading span. *Developmental science*. 2010; 13:779–789. [PubMed: 20712744]
- van den Berg R, Shin H, Chou WC, George R, Ma WJ. Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences*. 2012; 109:8780–8785.
- Van den Berg R, Awh E, Ma WJ. Factorial comparison of working memory models. *Psychological Review*. 2014; 121:124–149. [PubMed: 24490791]
- Zhang W, Luck SJ. Sudden death and gradual decay in visual working memory. *Psychological Science*. 2009; 20:423–428. [PubMed: 19320861]
- Zhang W, Luck SJ. The number and quality of representations in working memory. *Psychological Science*. 2011; 22:1434–1441. [PubMed: 21987693]

Research Highlights

- Working memory development in childhood has often been attributed to the role of increasing world knowledge, and that role was re-examined here using short-term recognition memory of an item within an array of English letters or unfamiliar characters.
- With the level of performance for the two types of stimuli equated in 7-year-old children, the advantage of known English letters over unfamiliar characters was less in that age group than it was for older children and adults.
- From third grade to adulthood, there was no further developmental change in the role of letter knowledge, but there was still a large increase in working memory performance. In a subgroup with sufficient letter knowledge, the pattern of increases across all four age groups in normalized capacity scores was the same for letters and unfamiliar characters.
- The results indicate that capacity, and not only knowledge or use of strategies, increases with age.

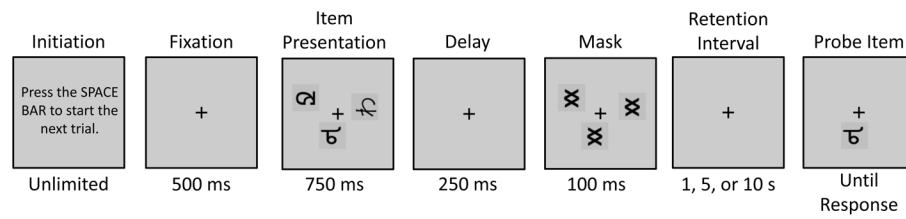


Figure 1.

An illustration of a test trial in the unfamiliar-character condition. In the English letter condition, there were five letters instead of three characters, to make the levels of performance more comparable across conditions.

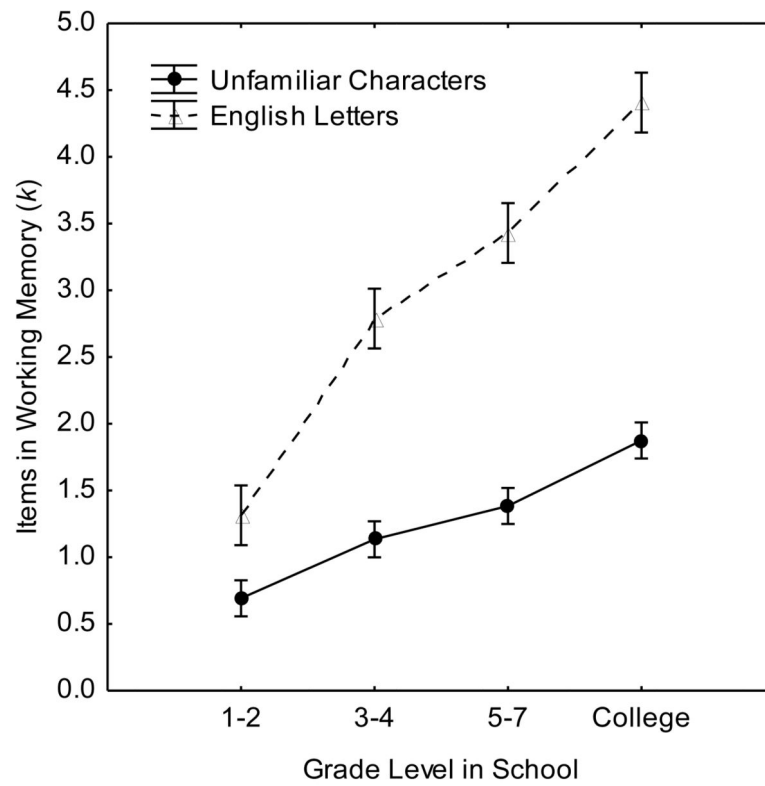


Figure 2.

Performance in each age group at the 1-s retention interval in terms of k , the estimate of the number of items in working memory (Cowan, 2001), for trials with unfamiliar characters and English letters. Age group is described according to the grade level in school, with ages of the four groups averaging about 7, 9, 12, and 25 years. Error bars are standard errors.

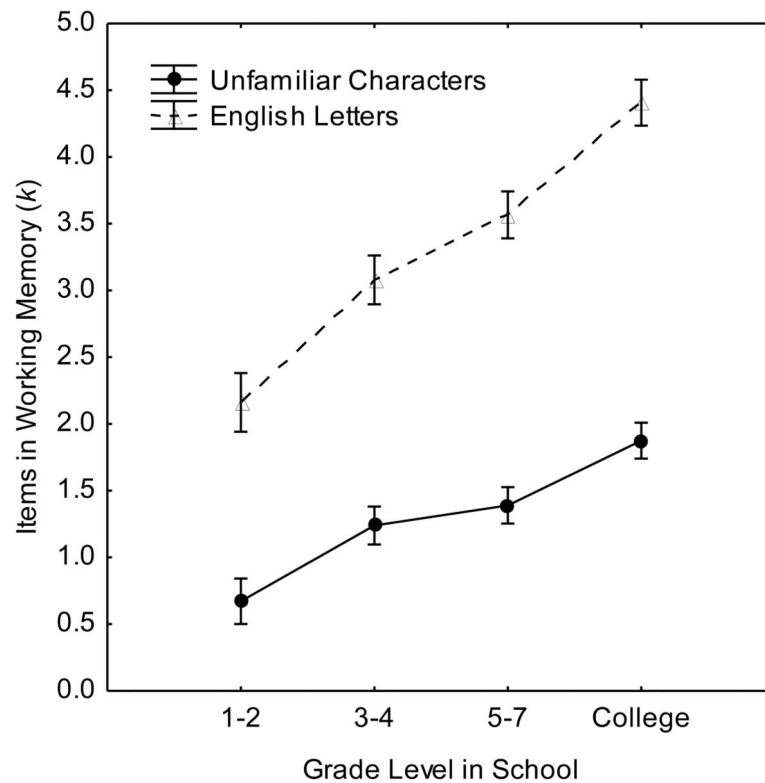


Figure 3.

For just those participants with a k of at least 1.0 in the letter condition at the 1-s retention interval: performance in each age group at the 1-s retention interval in terms of k , the estimate of the number of items in working memory (Cowan, 2001), for trials with unfamiliar characters and English letters. Age group is described according to the grade level in school, with ages of the four groups averaging about 7, 9, 12, and 25 years. Error bars are standard errors.

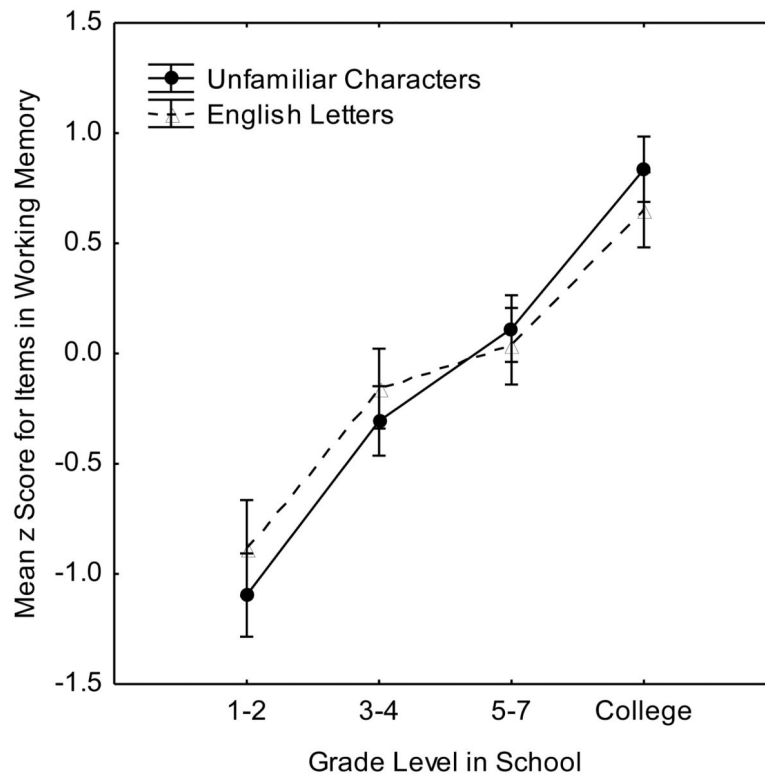


Figure 4.

Performance at 1-s intervals for participants with a k value of 1.0 or greater, in terms of the mean z score of k , the estimate of the number of items in working memory (Cowan, 2001). Each z score was calculated across all age groups, separately for characters and letters. Age groups are described according to grade level in school with levels averaging about 7, 9, 12, and 25 years of age). Error bars are standard errors.

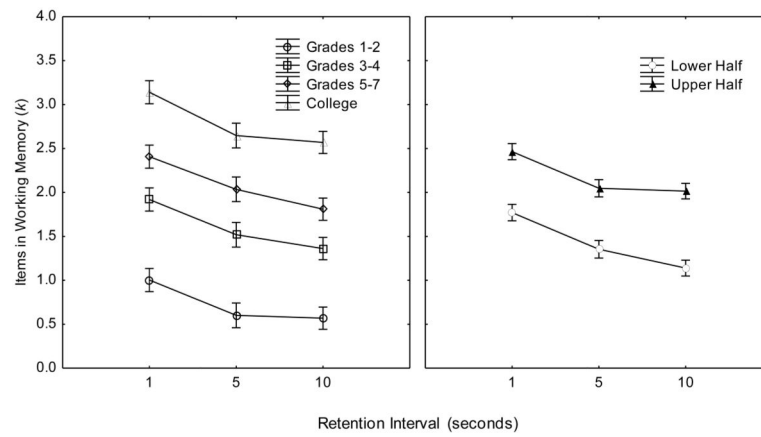


Figure 5.

Items in working memory, or k (Cowan, 2001) as a function of the retention interval. Left-hand panel: graph parameter is the grade level in school, with levels averaging about 7, 9, 12, and 25 years of age. Right-hand panel: graph parameter is the upper versus lower half of participants within each age group in terms of overall proportion correct. Error bars are standard errors.

Table 1

Mean proportion correct and SEM for each condition in the experiment.

Stimuli	Retention Interval	Change?	Grades 1–2		Grades 3–4		Grades 5–7		College	
			Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Characters	1 s	yes	.57	.03	.72	.03	.63	.03	.77	.03
		no	.66	.03	.66	.03	.83	.03	.86	.03
		yes	.69	.03	.75	.03	.77	.03	.87	.03
	5 s	no	.45	.03	.50	.03	.58	.03	.61	.03
		yes	.69	.03	.79	.03	.79	.03	.88	.03
		no	.42	.04	.43	.04	.47	.04	.50	.04
Letters	1 s	yes	.59	.03	.79	.03	.84	.03	.95	.03
		no	.67	.03	.77	.03	.85	.03	.94	.03
		yes	.63	.03	.80	.03	.86	.03	.95	.03
	5 s	no	.52	.04	.66	.04	.75	.04	.83	.04
		yes	.69	.03	.85	.03	.86	.03	.97	.03
		no	.47	.04	.58	.04	.70	.04	.84	.04

Table 2

Mean Items in Working Memory (*k*) and SEM for each condition in the experiment.

Stimuli	Retention Interval	Grades 1–2		Grades 3–4		Grades 5–7		College	
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Unfamiliar Characters									
	1 s	0.69	0.13	1.13	0.17	1.38	0.12	1.88	0.11
	5 s	0.43	0.13	0.78	0.14	1.06	0.13	1.43	0.14
	10 s	0.34	0.14	0.63	0.12	0.80	0.15	1.12	0.14
English Letters									
	1 s	1.31	0.25	2.79	0.24	3.43	0.23	4.41	0.16
	5 s	0.77	0.23	2.31	0.32	3.01	0.27	3.86	0.19
	10 s	0.80	0.21	2.15	0.25	2.82	0.29	4.02	0.21